HYBRID SYSTEM
GMSK DIGITAL RECEIVER IMPLEMENTATION
IN
REAL TIME/

A Thesis Presented to
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Ohio University

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of the Requirement for the Degree
Master of Science

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<td>analog-to-digital</td>
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<td>ADF</td>
<td>automatic directional finder</td>
</tr>
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<td>AM</td>
<td>amplitude modulation</td>
</tr>
<tr>
<td>ARINC</td>
<td>Aeronautical Radio, Incorporated</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>ATCRBS</td>
<td>Air Traffic Control Radar Beacon System</td>
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<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<td>AWOS</td>
<td>Automated Weather Observing System</td>
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<td>BDE</td>
<td>Block Diagram Editor</td>
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<td>BER</td>
<td>bit error rate</td>
</tr>
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<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>$B_r$</td>
<td>3 dB Gaussian Bandwidth</td>
</tr>
<tr>
<td>b /s</td>
<td>bits / second</td>
</tr>
<tr>
<td>CCD</td>
<td>charge coupled device</td>
</tr>
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<td>CGS</td>
<td>Code Generating System</td>
</tr>
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<td>D / A</td>
<td>digital-to-analog</td>
</tr>
<tr>
<td>dB</td>
<td>decibel</td>
</tr>
<tr>
<td>DME</td>
<td>Distance Measuring Equipment</td>
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<td>DPSK</td>
<td>Differential Phase Shift Keying</td>
</tr>
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<td>DSP</td>
<td>digital signal processor</td>
</tr>
<tr>
<td>$E_b / N_o$</td>
<td>bit energy / noise ratio</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>$f_c$</td>
<td>carrier frequency</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
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<tr>
<td>$f_d$</td>
<td>frequency deviation</td>
</tr>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulation</td>
</tr>
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<td>FSK</td>
<td>Frequency Shift Keying</td>
</tr>
<tr>
<td>GA</td>
<td>General Aviation</td>
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<td>GLPF</td>
<td>Gaussian Lowpass Filter</td>
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<td>GMSK</td>
<td>Gaussian Minimum Shift Keying</td>
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<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
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<td>IF</td>
<td>intermediate frequency</td>
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<td>ISI</td>
<td>intersymbol interference</td>
</tr>
<tr>
<td>kHz</td>
<td>Kilohertz</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
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<td>MOPS</td>
<td>Minimum Operational Performance Standards</td>
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<td>MSE</td>
<td>mean square error</td>
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<td>MSK</td>
<td>Minimum Shift Keying</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NFS</td>
<td>Network File System</td>
</tr>
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<td>Abbreviation</td>
<td>Description</td>
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<td>NRZ</td>
<td>Non Return to Zero</td>
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<td>NTSB</td>
<td>National Transportation Safety Board</td>
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<td>NWS</td>
<td>National Weather Service</td>
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<td>OQPSK</td>
<td>Offset Quadrature Phase Shift Keying</td>
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<tr>
<td>PC</td>
<td>personal computer</td>
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<tr>
<td>Pe</td>
<td>Probability of Error</td>
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<td>PM</td>
<td>phase modulation</td>
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<td>PSD</td>
<td>Power Spectral Density</td>
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<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>SFSK</td>
<td>Sinusoidal Frequency shift keying</td>
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<td>SNR</td>
<td>signal to noise ratio</td>
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<td>SPB</td>
<td>Signal Processing Block</td>
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<td>SPW</td>
<td>Signal Processing Workstation</td>
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<td>TDWR</td>
<td>Terminal Doppler Weather Radar</td>
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<td>VCO</td>
<td>Voltage Controlled Oscillator</td>
</tr>
<tr>
<td>VOR</td>
<td>Very High Frequency Omnidirectional Range</td>
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<td>VHF</td>
<td>very high frequency</td>
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Chapter 1

INTRODUCTION

In the implementation of a communications or signal processing system, it is important to perform a simulation using a model of the system. This allows for the partial characterization of the system as it would work in a real time environment. With the essential design criteria necessary to model a system, a simulation is developed. The system is required to meet certain specifications and with the help of a model simulation, it can be stated with a certain degree of accuracy that the real time implementation system will meet the required specifications.

Once the simulation step is fulfilled and the model system is known to meet the desired performance criteria, the system needs to be implemented in real time. Most of the systems built with communications or a signal processing applications in mind are constructed using such steps. By a real time application we mean that the system can process information at a rate equal to that of the data generation rate. Usually a system model developed for simulation purposes does not necessarily meet the real time constraints. Many modifications are required to be made by the design engineer to meet the real time design requirements imposed on the system development.

It would, however, be a significant accomplishment, if a simulated model could directly be replaced by a real time system. This would greatly reduce development time for the real time system from the simulated model. In effect, a
design implementation of a specific system can be proposed, imposing performance characteristics on the system. Then a simulation model of the proposed system can be constructed with the real time implementation of the system as the final goal. The final simulated model should then be directly converted into a system that can perform real time computations. The above steps are as shown in Figure 1.1.

Keeping the above ideas in mind, a groundwork has been established by this paper. A sophisticated software-based simulator called the Signal Processing Workstation (SPW) used for simulating signal processing and telecommunications systems, is applied to a specific problem, namely development of a receiver structure for phase modulation of the hybrid modulation system. Briefly, hybrid modulation is a single carrier wave being both phase modulated and amplitude modulated. With the use of SPW, an unparalleled degree of freedom is available for the user to simulate systems. An additional element of SPW is the Code Generating System (CGS) which generates a C program for many DSP microprocessors, thus allowing the transition from simulation to real time systems. Next, the C program generated by the CGS was modified to enable stand-alone execution on a TI-DSP board located inside a Personal Computer (PC). The DSP board provides analog signal inputs and outputs which were used to modulated and demodulate a radio frequency (RF) carrier signal in real time.

1.1 Signal Processing Workstation (SPW)

Various digital signal processing (DSP) designs can be interactively captured,
Figure 1.1 Block Diagram Representation of Steps in Designing/Implementing a System
simulated, tested and implemented using the tools provided by SPW (SPW - User’s Guide, 1994). It provides a graphical user interface for all aspects of system design, simulation, and implementation. The software is divided into program modules that can run simultaneously under a multi-tasking environment on the computer Workstation. The Block Diagram Editor (BDE) is the basic design environment for DSP system. It is a program that starts whenever SPW is initiated on the Workstation. In this window various blocks, such as filters, integrators, etc. can be linked with the help of wires and connectors to simulate a system design. The signals generated by the simulation can be viewed on a Signal Calculator, another program module of SPW. The Signal Calculator can also edit, create, process and analyze all types of signal waveforms.

1.2 Code Generating System (CGS)

Once the design and simulation of a system have been completed using the BDE and Signal Calculator tools of SPW, a powerful tool called the Code Generating System (CGS), can be used to generate a C program (SPW - User’s Guide, 1994). This code can then be executed on various DSP chips for real time implementation of SPW algorithms. CGS converts a block diagram designed on the BDE into an executable C program and thus one can develop, debug and port DSP designs quickly and easily.

The DSP microprocessor board is located in a host PC. The SPW Workstation is connected to the PC via an Etherlink, using the Network File System
(NFS) for transferring files. The PC is used for compiling the DSP C code. The C code is then transferred and executed on the DSP microprocessor board. The various commands for compilation and execution of the C code can either be controlled from the Workstation or from the PC directly. Executing the control commands from the PC directly allows for more flexibility in terms of real time applications.

Figure 1.2 is a diagram showing the operation of the CGS with compilation and execution of the C code occurring on a PC-based development system. Beginning from the design file, as generated by the BDE, CGS generates a software program in C. Using commands under the CGS control windows, the C code generated can be downloaded on to the PC development board. It is then compiled on the PC and executed on the DSP microprocessor located in the PC. The output signals, as generated by the DSP microprocessor on the PC development board, can be viewed on the Workstation using the Signal Calculator. Thus, the system design can be tested and modified accordingly.

1.3 Applications of CGS

A brief overview of how CGS works is presented in Section 1.2. Using the combined efforts of SPW and CGS, various systems related to signal processing and communications can be designed and implemented in real time. Two example applications are discussed in the next two sections. Following these examples, the design of a phase demodulator for the hybrid system is pursued, in which the
Figure 1.2 Description of Remote Compilation/Execution using CGS
technical capabilities of SPW and CGS are mentioned in detail.

1.3.1 Global Positioning System Simulations (GPS)

Various industries are looking into employing SPW and CGS for simulation of various receiver structures that would demodulate the signals received from satellites. The Global Positioning System consists of a constellation of 24 satellites that allow a user situated on earth to know her/his position to within 100 meters of accuracy. A receiver is required by the user to demodulate the received signal from the satellite.

Currently Stanford Telecom Inc., is looking into the possibilities of using CGS and SPW for GPS simulation facilities. They have developed, for NASA, the prototype of a new receiver that combines the most advanced charge coupled device (CCD) technology with powerful digital signal processors, to provide unmatched operational flexibility in a single self-contained unit.

1.3.2 Design of VOR Transmitter for a Digital Data Broadcast

VOR stands for very high frequency omnidirectional range, and is the International Civil Aviation Organization (ICAO) standard for providing short-range enroute bearing information to aircraft in flight. It is a radial determining navigation aid, and along with the Distance Measuring Equipment (DME) is the most popular system currently in use. Since VOR is a radial system, it must have a reference signal along with a signal that carries the bearing information. The
reference signal is frequency modulated (FM) at 30 Hz on a 9960 Hz subcarrier. A cardioid antenna pattern rotates 30 times per second, generating 30 Hz amplitude modulation, thus providing bearing information. The airborne receiver then decodes bearing as a function of the phase difference between the FM reference signal and the AM modulated signal.

Currently, research is underway at the Ohio University Avionics Engineering Center to use the capabilities of CGS and SPW to investigate the use of the VOR spectrum to broadcast digital data for a Global Positioning System (GPS) based aircraft landing system. The basic implementation is to use a Special Category 1, commonly termed SCAT 1 system, to send corrections to the aircraft from the ground-based terminal using a data broadcast. This data can be then used to improve upon the positioning information necessary for landing aircraft.

1.3.3  Implementation of a Phase Transceiver Structure for the Hybrid System

The use of real time weather data display in the cockpit will greatly help in avoiding major accidental situations that have been taking place practically from the beginning of aviation history. Accidents caused by the unavailability of real time weather data to the pilot are rated second, preceded by pilot error, as reported by the latest statistics given by the National Transportation Safety Board (NTSB) (National Transportation Safety Board, 1991).

As airways become more and more crowded worldwide, improved weather information is a solution to maintaining flight safety and lowering operational costs.
A group of organizations including: Advanced Satellite Telecommunications, Inc., Conwal, Inc., Garcia Consulting, ARINC, Lockheed, FAA, and NASA, have come together to resolve this problem. Several methods were put forward by the group to display real time weather data for both civilian and military users (Hart, 1993). They intend to use satellites, weather estimation software, cockpit avionics, etc. to accomplish this task. The proposed system would use an on board receiver to demodulate the data from the satellites. These on board receivers are expected to be simple and cheap.

At present, the pilot of a General Aviation (GA) aircraft can only obtain weather data through voice communication. During landing, takeoff, and congested traffic conditions, Air Traffic Control (ATC) is often unable to supply the pilot with the necessary weather data information that he might need to make a go/no-go decision (National Transportation Safety Board, 1986). In addition, the voice data information provided to the pilot is extremely limited and a better system must be developed; one that would not affect the existing system and simultaneously provide the pilot with real time weather information.

A study done by Craig Parker at the Ohio University Avionics Engineering Center shows that such a system can be implemented. In the course of the study, a weather data dissemination system was developed. This system obtains weather radar reflectivity patterns, digitizes the image, compresses and transmits the data over a standard VHF aeronautical channel to enroute aircraft. On board the aircraft the data is demodulated and processed so that the image can be displayed using an
Craig Parker also analyzed a hybrid modulation technique, where a single carrier frequency is modulated by both an analog voice signal (using amplitude modulation) and digital weather data (using phase modulation). He selected Minimum Shift Keying (MSK) for the digital modulation of the weather data.

This work was then followed up by Dennis Akos. In his study he established that a new modulation scheme, referred to as Gaussian Minimum Shift Keying (GMSK), would cause less interference to the AM voice communications. The GMSK modulation technique was introduced for use in the field of digital mobile radio telephony. The European Conference of Postal and Telecommunications Administration selected this type of modulation scheme for the Pan-European Cellular Radio System (McGrath, and Burkley, 1990). It is evident from the study done by Dennis Akos that the use of GMSK for the phase modulation of the hybrid system would improve performance. A GMSK transmitter was then developed that used a PC-based two-channel DSP board. This DSP board generates the inphase and quadrature phase components of the GMSK signal at baseband. These signals thus generated would perform the phase modulation on the transmitted carrier wave. The resulting signal could then be amplitude modulated using the existing AM transmitter. The transmitted hybrid signal requires demodulation, where the signals of interest are the phase modulated digital data and the amplitude modulated voice waveform (Akos, 1992).

The use of SPW can be employed to simulate the complete hybrid system
using GMSK for phase modulation. The use of CGS can be made to implement the
designed GMSK phase demodulator in real time. It is the purpose of this paper to:
(1) Discuss the various transceiver structures for the phase modulation/demodulation
incorporated in the hybrid system. (2) Design various transceiver structures and
simulate these structures to evaluate performance using SPW  (3) Select the model
which best meets the requirements for the hybrid system (4) Design an experimental
setup that receives the phase modulated data and performs demodulation by using
CGS and implement the system in real time.
Chapter 2

SPECTRALLY EFFICIENT PHASE MODULATION TECHNIQUES

The demand for radio frequency spectrum is increasing rapidly, which necessitates the development of techniques for the efficient use of the available spectrum. In order to transmit weather data, a major revision of the existing system currently in use would be necessary. One possible improvement entails the replacement of existing 25 KHz amplitude modulated (AM) voice channels with 5 KHz phase modulation (PM) digitized voice, thus increasing the number of available channels by five. This would, however, require the replacement of the existing base of transmitters and receivers. Another way of approaching the problem would be to increase the number of channels in the radio frequency domain. This would allow existing equipment to be used. However, this is not a practical solution to the problem since the radio channels are already in demand and strictly controlled. The addition of a spectrally efficient phase modulation technique to the existing AM channels would, in theory, not affect the current base of receivers and provide weather data in the cockpit. This type of technique where both amplitude and phase modulation is performed on the signal is called hybrid modulation (Benelli, Fantacci 1983). This application would require strict constraints that do not affect or degrade the existing system. It is possible to do this by closely examining the various digital phase modulation techniques and their effects on the existing system.

The study by Benelli and Fantacci was pursued by Craig Parker (Parker,
1989) and was followed up by Dennis Akos (Akos, 1992). The various considerations made in the selection of the phase modulation technique for the hybrid system will be summarized in this chapter. Also, the various digital phase modulation techniques will be discussed in this chapter.

2.1 Benelli and Fantacci Study

This paper was the first to investigate the hybrid modulation approach. In theory it was assumed that the two modulations, amplitude and phase, are independent of each other. The practical system was, however, shown to have interference between the two modulation techniques imposed on the same carrier and associated communication parameters. The primary cause of interference was due to bandlimitation of the transmitted hybrid signal. The initial work was done by Benelli in which he looked at the various phase modulation techniques and the effect it would have on the existing AM signal.

Benelli chose to investigate different types of phase modulations, such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK) and Minimum Phase Shift Keying (MSK). The hybrid signal incorporated these techniques in the phase modulation component and this was used for trials consisting of four seconds of simulation time. The channel itself was assumed to be noiseless, so any distortion introduced into the AM signal could be attributed only to the additional phase modulation. A modulation index of 0.9 was used and data rates between 300 and 2400 b/s were tested. The resulting signal-to-noise ratios (SNR),
in dB, were calculated and are shown in Table 2.1 (Benelli, 1982). From the results obtained it is clear that MSK outperforms QPSK at all data rates as far as the output AM SNR is concerned.

The AM-MSK system also proved to be slightly better in performance to the AM-QPSK system when comparisons of the bit error rate probabilities were made. Although here, the difference was marginal between the two implementations. Both systems showed a loss of only 2-4 dB as with respect to the case of infinite bandwidth and constant envelope data modulation (Bennelli, 1982). In the various simulations performed by Benelli and Fantacci, they found that the degradation in the AM portion of the hybrid system was due to the spectral spread of the phase modulation used. Those phase modulations with a wide power spectrum resulted in a low AM SNR, except at the lowest bit rate tested. However, the MSK phase modulation, which has a narrow power spectrum, provided an AM SNR of greater than 30 dB for all cases.

An important factor that was not studied by Benelli and Fantacci was the Doppler effect on the received signal. This has the effect of shifting the frequency of the carrier signal, due to the aircraft dynamics. This would cause additional degradation in the system performance, particularly the BER. According to their study it was pointed out that the relevance of the Doppler effect depends on the design of the transmitting and receiving filters. A comprehensive study of the AM-MSK system was done, using various bit rates for the MSK portion of the system. Their study was concluded with the testing of an AM-MSK system, which provided
Table 2.1 Signal to Noise Ratios at the AM Detector Output
(Benelli, 1982)

<table>
<thead>
<tr>
<th>Data Rate (bits / sec)</th>
<th>AM-QPSK (dB)</th>
<th>AM-MSK (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>15.3</td>
<td>35.6</td>
</tr>
<tr>
<td>600</td>
<td>12.4</td>
<td>35.6</td>
</tr>
<tr>
<td>1200</td>
<td>9.3</td>
<td>35.3</td>
</tr>
<tr>
<td>2400</td>
<td>-</td>
<td>31.6</td>
</tr>
</tbody>
</table>
satisfactory results at 2400 b/s.

2.2 Parker’s Study

Parker proposed that the hybrid modulation scheme could be used for weather data dissemination. Following the studies done by Benelli and Fantacci, he noted that a hybrid system using MSK for phase modulation could be used to transmit digital data up to 2400 b/s. The data rate of 2400 b/s is important as this is equivalent to that rate used in the experimental system to uplink weather graphics using only phase modulation. Parker proceeded to predict the transmitted bit energy-to-noise ratio $E_b/\!\!N_o$, as a function of the existing intermediate frequency (IF) $S/N$ at the minimum received power level allowed within a defined coverage area. This is important as it allows under the limits of radio coverage the bit error probabilities to be predicted for the phase modulation portion of the hybrid signal. The result of the analysis is presented in equation (2.1)

$$\frac{E_b}{N_o} = 10 \log \left[ \frac{B \left( 1 - \mu_{\text{max}} \right)^2}{R \left( 1 + \frac{\mu^2}{2} \right)} \right] + \left[ \frac{S}{N} \right]_{IF}$$

(2.1)

where:

- $B$ is IF bandwidth
- $R$ is the data rate
- $\mu$ is the index of modulation

Using the parameters consistent with the analysis, Parker found that an $E_b/\!\!N_o$ of
13.8 dB could be obtained (Parker, 1989). From the work done by Benelli and Fantacci, it was found that a maximum loss of approximately 4 dB occurs due to the hybrid modulation technique. Therefore, the resulting ratio is 9.8 dB. Using this ratio with the probability of bit error as given by equation (2.2) and plotted in Figure 2.1, it can be seen that a BER value of $10^{-5}$ can be achieved. This is an acceptable worst case figure.

$$P_E = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\lambda^2} d\lambda$$  \hspace{1cm} (2.2)$$

In his analysis, Parker also verified that the frequency range occupied by the power spectrum of the hybrid signal would meet the standards set by the Federal Communication Commission (FCC) (Parker, 1989). He convolled the base band spectrum of the MSK signal, which was frequency shifted and amplitude scaled, with the power spectral density (PSD) of a simulated voice signal which resulted in the power spectral density as shown in Figure 2.2. It was evident that the power spectrum of the hybrid signal meets the requirements for spectral allotment.

2.3 Akos Study

The work done by Benelli and Fantacci set the base for a hybrid modulation signal that would combine both amplitude and phase modulation on a single carrier. Parker took this work a step further, proposing its use for a weather data uplink system. However, there were various items that needed special attention as to
Figure 2.1 Probability of Bit Error for MSK Signal
Figure 2.2 Hybrid Power Spectral Density and FCC limits
ensure that the proposed system could be implemented successfully. These include:

1) have a receiver structure which would be insensitive to Doppler shift, to
demodulate the phase modulation of the hybrid signal; 2) Consider the carrier
stability related to the data rate of the signal used for phase modulation (Pasupathy,
1979); 3) Improve on the phase modulation technique by using recently developed,
spectrally efficient schemes to further reduce distortion of the AM channel.

Dennis Akos at the Ohio University Avionics Engineering Center continued the study done by Craig Parker, giving special attention to these three items. His main area of concentration was to apply a spectrally efficient phase modulation scheme that would minimize the AM distortion and at the same time would enhance the hybrid modulation scheme. A detailed study was done concerning the various phase modulation methods that could be used for the hybrid system.

The results Akos' work show that a MSK implementation requires that the carrier frequency be an exact multiple of one-quarter of the bit-rate. If this is not followed, then a variation in the amplitude modulation would result in further degrading the performance of the amplitude modulation. For the weather data application it is not possible to use a value for the carrier frequency, as assigned to the VHF AM communication channels, that would meet the MSK requirements. Therefore the use of MSK on these channels would introduce further degradation into the AM signal.

Also, a major source of error in the implementation of the hybrid system is the Doppler effect. This effect is seen when the receiver is placed on a mobile
platform, such as an aircraft, which results in a shift in the received frequency. The phase modulated carrier can be demodulated using both coherent and non-coherent detection. In coherent detection a synchronized reference is required while in non-coherent detection such synchronization is not necessary. The advantage of using a coherent type of detection is that it provides improved BER performance as compared to non-coherent types of detection. MSK demodulation is done primarily using coherent detection technique, although a non-coherent detection scheme can also be employed. An MSK system using a non-coherent detection scheme would be preferred as to minimize the effect of the Doppler shift for the proposed hybrid system, but this results in a degradation of the BER performance. Akos proposed a modulation scheme that would result in less AM degradation, would allow use of a non-coherent detection scheme, and allow the hybrid system to be implemented under the restrictions as applied due to the bandwidth containment in the frequency spectrum.

This type of phase modulation scheme, which uses a non-coherent type of detection and can be implemented under no strict relationship between the carrier frequency and the data rate while maintaining the spectral containment limitation is called Gaussian Minimum Shift Keying Receiver (GMSK). The study established the fact that the bit transitions of the phase modulation signal directly affect the power spectrum of the transmitted signal. It was made clear in this study that if somehow these phase transitions in the data phase modulating the carrier signal could be smoothened, then a spectrally efficient hybrid system could be
implemented. A detailed study of the phase functions of QPSK, OQPSK, SFSK, MSK and GMSK signals was performed. The phase functions of SFSK and GMSK were free of any sharp transitions. These two modulation methods thus formed the best candidates for phase modulation for the hybrid system.

To select the more appropriate modulation scheme for the particular application, a simulation was performed. This simulation incorporated the use of the contending phase modulation techniques, namely GMSK, MSK, SFSK and QPSK into the hybrid system. The degradation in the voice channel was studied as this was the area of primary concern for the study of the existing system. The use of the Benelli and Fantacci study on the hybrid system was made to obtain the various parameters associated with the data uplink system (Fantacci, Benelli, 1983).

From the simulation results it was interpreted that for higher spectral efficiency a higher data rate could be used. The 99% bandwidth energy containment of SFSK was greater than MSK, thus showing that SFSK does initially have a faster sidelobe reduction than MSK (Akos, 1992). However, SFSK does not respond well to filtering, used in the hybrid system both at the transmitter and receiver end, due to a significant amount of high-frequency energy. GMSK, however, showed acceptable mean squared error of the AM voice signal (MSE) results up to a data rate of 3900 b/s, an increase of over 60% as compared with any previous work. Also, GMSK has a good spectral efficiency with the sidelobes occupying a very small area in the power spectrum. Therefore, it was concluded that GMSK would improve performance when used for the phase modulation in the
hybrid system.

A test system of the phase modulator part was set up by Akos. To achieve the transmission of a hybrid signal without modifying the AM part of the system, it was proposed that a Vector Modulator chip be used, which is a commercially available chip (Merrimac). The set up is as shown in Figure 2.3. The carrier signal is split into the inphase and quadrature phase components thus allowing the in phase and quadrature phase of the digital data to phase modulate the carrier. The inphase component, I(t), and quadrature phase component, Q(t), are generated by using a digital signal processing (DSP) board, which generates the required signals in real time. The resultant signal can then be amplitude modulated to form the overall hybrid signal.

2.4 Receiver Implementation

Now that a transmitter for the hybrid system was developed a study into the various receiver structures, best suited for the phase demodulation of the hybrid signal was required. Akos' study established the grounds for the design and implementation of a phase transceiver model that would improve and also not change the existing system. A Gaussian phase modulator that used the real time capabilities of a DSP board was developed. On similar grounds, a Gaussian demodulator is required to be developed which would overcome the effects of Doppler shift and other discrepancies, as mentioned in section 2.3 of this chapter.
Figure 2.3 Transmitter Modification for Generation of the Hybrid Signal
The capabilities of the Signal Processing Workstation (SPW) were briefly mentioned in section 1.1 of Chapter 1. The use of this software provides powerful tools that make it possible to perform various simulations concerning many systems related to the communications field. Also the performance analysis of the various transceiver structures of the phase modulation/demodulation of the hybrid signal can be analyzed to select the best receiver structure that would meet the required specifications. The next chapter presents the GMSK transceiver design. This chapter presents an analysis of the MSK coherent transceiver design implementation. The MSK transceiver was implemented first, because it was possible to verify the results against existing MSK performance results.

3.1 MSK Transceiver Implementation on SPW

The minimum shift keying type of receiver is simulated using the Signal Processing Work Station (SPW). The key advantage of doing this is the GMSK type of signal is a modified version of the MSK signal. Also the theoretical results, such as, BER curves, and various receiver implementations of both coherent and non-coherent types of receivers are readily available for MSK systems. This allows for the comparison and analysis of these systems and also provides a framework for designing a GMSK type of receiver, which is the final goal.
The equation of a transmitted MSK signal can be written as

\[ s(t) = a_I(t) \cos \left( \frac{\pi t}{2T} \right) \cos (2 \pi f_c t) + a_Q \sin \left( \frac{\pi t}{2T} \right) \sin (2 \pi f_c t) \] (3.1)

The various signal structures that form the transmitted MSK signal are shown in Figure 3.1 - Figure 3.3. The inphase signal \( a_I(t) \) is multiplied with a cosine signal, \( \cos \left( \frac{\pi t}{2T} \right) \) and then with the inphase of the carrier signal, \( \cos (2 \pi f_c t) \). A similar operation is performed on the incoming quadrature signal \( a_Q(t) \) and the resulting components are summed to obtain the transmitted MSK signal \( s(t) \).

The block diagram of a typical MSK transmitter is shown in Figure 3.4. This block diagram implements Equation 3.1. The signal, thus formed, needs to be demodulated at the receiver end. This requires the design of a receiver that incorporates a carrier and also a bit synchronization circuit, since a coherent type of detection is employed.

The block diagram of a synchronization circuit used for this receiver structure is shown in Figure 3.5 and is known as Sunde’s FSK (Bennett, Rice 1963). The transmitted signal, as given in (3.1), is squared to give strong discrete frequency components at \( 2f_c \) and \( 2f_c \), where

\[ f_c = f_c + \frac{1}{4T} \] (3.2)

and
Figure 3.1 Inphase Signal Weighted with Sinusoidal Pulses

Figure 3.2 Quadrature Phase Signal Weighted with Sinusoidal Pulses
Figure 3.3 Transmitted MSK Signal
Figure 3.4  MSK Modulator
Figure 3.5 Synchronization Circuit
Two Phase Locked Loops (PLL) are used, which individually perform the function of a Bandpass filter followed by a frequency divider (Bennet, Rice 1963). As a result we have the signals \( s_1(t) \) and \( s_2(t) \) where

\[
s_1(t) = \frac{1}{2} \cos \left( 2 \pi f_c t + \frac{\pi t}{2T} \right)
\]

(3.4)

\[
s_2(t) = \frac{1}{2} \cos \left( 2 \pi f_c t - \frac{\pi t}{2T} \right)
\]

(3.5)

respectively.

Thus the synchronization circuit gives the reference carriers \( x(t) \) and \( y(t) \) which is the sum and difference of \( s_1(t) \) and \( s_2(t) \) where

\[
x(t) = \cos \left( \frac{\pi t}{2T} \right) \cos \left( 2 \pi f_c t \right)
\]

(3.6)

and

\[
y(t) = \sin \left( \frac{\pi t}{2T} \right) \sin \left( 2 \pi f_c t \right)
\]

(3.7)

\( s_1(t) \) and \( s_2(t) \) are fed through a lowpass filter in order to get the clock signal. The output of the lowpass filter is at twice the bit rate. The threshold detector is used to reduce the frequency of the incoming signal by half. The rising edge true block gives impulses at the desired bit rate.
The MSK receiver as implemented on SPW is shown in Figure 3.6. The two signals, \( x(t) \) and \( y(t) \), generated by the synchronization circuit are multiplied by the incoming signal \( s(t) \). The clock signal output of the synchronization circuit is shown in Figure 3.7. There is a certain amount of delay due to the PLL operation and filtering in the synchronization block. This delay is compensated for at the receiver end, as shown by the delay block in Figure 3.8. The energy for a given bit period is collected by the integrate and dump circuit and the output of the integrate and dump circuit is shown in Figure 3.8. The output is then fed to the sample and hold edge trigger circuit which holds the output of the integrate and dump circuit for one-bit period. The decision is then made on both the inphase and quadrature phase components by the decision block.

The outputs from the decision blocks, both for the inphase and quadrature phase components, are shown in Figure 3.9 and Figure 3.10. These are compared with the input inphase and quadrature phase components at the transmitter end as shown in Figure 3.11 and Figure 3.12. Therefore, it is seen that both the input and output signals match, justifying that the receiver is operating satisfactorily. Next, it is necessary to compare the performance of the above designed receiver with that of theoretical data for a signal with Additive White Gaussian Noise to verify whether the design is correct.

3.2 Evaluation of the Average Probability of Bit Error using AWGN Channel

The probability of bit error for the simulated system is evaluated as follows.
Figure 3.6 MSK Coherent Receiver
Figure 3.7 Clock Signal

Figure 3.8 Integrator & Dump Output for Quadrature Phase Signal
Figure 3.9 Inphase Output Signal

Figure 3.10 Quadrature Output Signal
Figure 3.11 Inphase Input Signal

Figure 3.12 Quadrature Input Signal
Let

\[ P_s = \text{Average power of the transmitted signal} \]

\[ P_n = \text{Average noise power injected into the system} \]

\[ \sigma^2 = \text{variance of the noise injected into the system} \]

\[ R = \text{data rate of the transmitted digital signal} \]

\[ f_s = \text{sampling frequency at which the system is simulated} \]

\[ N_o \quad \text{is the one-sided spectral noise density} \]

The bit energy is given by

\[ E_b = \frac{P_s}{R}; \quad (3.8) \]

The noise power is given as (Couch, 1989)

\[ P_n = N_o \times f_s \quad (3.9) \]

For complex noise, the noise power is given by twice the variance of the noise

\[ P_n = 2 \times \sigma^2; \quad (3.10) \]

and therefore combining equations (3.9) and (3.10), we get

\[ 2 \times \sigma^2 = N_o \times f_s \quad (3.11) \]

Therefore

\[ N_o = \frac{(2 \times \sigma^2)}{f_s} \quad (3.12) \]
Combining (3.8) and (3.12)

\[
\frac{E_b}{N_o} = \frac{(P_s \times f_s)}{(2 \times \sigma^2)}
\]

(3.13)

We can find \( P_s \) by adding a complex average power estimator at the point where the signal is being transmitted in the simulated system. Also, the sampling frequency and the variance of the injected noise are known. Thus, we can calculate the \( E_b / N_o \) being used in the simulation. This is plotted on the x-axis in dB scale and the probability of error is obtained from the error counter module of SPW.

3.4 Performance Evaluation

In order to test the receiver under noisy conditions a white noise block is incorporated between the transmitter and the receiver whose variance is specified as a simulation parameter. The block diagram for such a system is shown in Figure 3.15. The incoming inphase and quadrature phase components are compared with the outgoing inphase and quadrature phase components, respectively. Thus, each bit is compared to check the probability of error in the system. A BER curve was plotted to verify the results of the designed system. The theoretical formula for a MSK BER evaluation (Couch 1989) is given by

\[
P_e = Q \left( \sqrt{2 \left( \frac{E_b}{N_o} \right)} \right)
\]

(3.14)

and plotted in Figure 3.13. The theoretical and simulated curves are compared as shown in Figure 3.14. From Figure 3.14, it was interpreted that the simulation
adequately represents a true MSK system as far as the BER curves were concerned. In Figure 3.14, an erroneous simulated point is obtained that falls on the left hand side of the theoretical BER curve. This is not possible in an actual implementation. The erroneous simulated point has resulted due to the fact that the number of bits counted for that particular simulation were not adequate in relation to the BER.

3.5 Conclusion

The purpose of designing and simulating the MSK transceiver was two fold: 1) To establish a base for the design of the GMSK receiver; 2) To demonstrate the capabilities of the SPW so that other communication systems can be simulated and verified. The various signal structures plotted and displayed on the signal calculator of the SPW software are included in this chapter to give a general idea of analyzing signal structures and performing various signal processing techniques.
Figure 3.13 Plot of Theoretical MSK BER Curve

Figure 3.14 Comparison of Theoretical & Simulated MSK BER Plots
Figure 3.15 MSK Coherent System for BER Evaluation
Chapter 4
Implementation of the GMSK Transceiver

Now that the process of design and simulation of a transceiver structure, namely the MSK coherent type of transceiver structure, was successfully realized on SPW and the performance criteria were matched to the theoretical BER curves, various other transceiver structures can be successfully designed and simulated using the same technique. The use of a coherent receiver for MSK is not practical in applications where the Doppler effect has a major effect on the received signal frequency. The Doppler effect causes severe BER degradation in the performance of a coherent type of implementation as it has negative effects on the synchronization circuit. Thus a system needs to be designed which would negate the effects of the Doppler shift. A non-coherent system can be used to overcome the effects of the Doppler shift. In such a system a synchronized reference to demodulate the incoming signal is not required, thus eliminating the need for a carrier synchronization circuit.

This chapter is concerned with the design of a Gaussian minimum shift keying (GMSK) type of receiver using differential non-coherent reception. Two types of differential detection schemes, one-bit and two-bit differential detections are discussed. With these types of detection schemes, a carrier synchronization circuit need not be developed and therefore the Doppler effect can be minimized. The receiver performance for the two detection methods is analyzed in the presence of an
Additive White Gaussian Noise, and the results are compared with the theoretical curve.

4.1 GMSK Receiver Design Implementation on SPW using a Two-bit Detection Scheme

The receiver designed on SPW is shown in Figure 4.1. The received signal is first passed through a complex spectral shifter and then through a GLPF. The complex spectral shifter shifts the frequency spectrum of the incoming signal into its low pass equivalent allowing Gaussian filtering. The 3-dB bandwidth of this GLPF, \( B_r \), is normalized to give optimum performance (Simon, Wang 1984). The filtered signal is then passed through a two-bit differential decoder, the details of which are shown in Figure 4.2. The output of the decoder is then passed through a low pass Butterworth filter whose 3-dB cutoff frequency is adjusted according to the baud rate of the transmitted signal. Hard decision is made at the output of this filter. The output of the low pass filter is also fed to the bit synchronization circuit whose operation is discussed in section 4.5 of this chapter. The threshold of the decision block is adjusted to obtain the optimum performance.

The operation of the receiver can be explained as follows (Simon, Wang 1984):

Let

\[
x(t) = \sqrt{S} \cos \left[ \omega_0 t + \theta(t) \right] + n(t)
\]

(4.1)
Figure 4.1  GMSK Receiver
where

\[ x(t) = \text{the signal at the input of the complex spectral shifter}, \]

\[ S = \text{signal power}, \]

\[ n(t) \text{ is the white Gaussian noise with one-sided spectral density } N_o, \]

\[ \omega_o = 2 \pi f_o \text{ is the center IF filter radian frequency}, \]

\[ \theta(t) \text{ is the transmit-filter data phase after frequency modulation.} \]

The Gaussian filter at the receiving end bandlimits \( x(t) \) which results in a time varying envelope \( x_{IF}(t) \), that is the sum of a \( \sqrt{2S} a(t) \), the distorted phase signal \( \phi(t) \), and a signal noise term \( n(t) \). The resultant is given by:

\[ x_{IF}(t) = \sqrt{2S} a(t) \cos \left[ \omega_o t + \phi(t) \right] + n(t) \quad (4.2) \]

Let \( n_z(t) \) and \( n_s(t) \) be independent lowpass zero mean Gaussian random processes.

Equation (4.2) in polar form is given as:

\[ x_{IF} = R(t) \cos \left[ \omega_o t \phi(t) + \eta(t) \right]; \quad (4.3) \]

where

\[ R(t) = \sqrt{\left(2S\right)} a(t) + n_z^2(t) + n_s^2(t) \quad (4.4) \]

and

\[ \eta(t) = -\tan^{-1}\left( \frac{n_z(t)}{\sqrt{\left(2S\right)} a(t) + n(t)} \right) \quad (4.5) \]
This signal is fed to the two-bit differential decoder. In the two-bit differential detector the incoming signal is multiplied by a version of itself that is delayed by twice the symbol time $T$, as shown in Figure 4.2 resulting in

$$y(t) = \frac{R(t) R(t - 2T)}{2} \cos \left[ 2w_ot + \Delta\phi(2T) \right]$$  \hspace{1cm} (4.6)$$

with

$$\Delta\phi(2T) = \phi(t) - \phi(t - 2T) + \eta(t) - \eta(t - 2T).$$

Assume that the carrier frequency is chosen such that

$$w_oT = 2\pi k,$$  \hspace{1cm}\text{where } k\text{ is an integer}

In which case equation (4.7) simplifies to

$$y(t) = \frac{R(t) R(t - 2T)}{2} \cos \Delta\phi(2T)$$  \hspace{1cm} (4.7)$$

The receiver then decides that a "1" was sent if $y(t) > 0$ otherwise it decides that a "0" was sent (Anderson, Bennett, Davey, Salz 1964). The eye opening for the two-bit detector is more than that of a one-bit detector and this can be used to give better performance. A dc bias, $q$, can be applied to the threshold input of the decision block that results in an improved system performance as far as the bit error rate is concerned. Therefore, with the application of the dc bias we can restate the decision rule as: decide that a "1" was sent if $y(t) > q$, otherwise decide "0".
Figure 4.2  Two-Bit Differential Decoder
Equation 4.7 reveals that \( y(t) \) is not directly related to the cosine term of the equation, but is also dependent on the envelope product \( R(t)R(t-T) \). In order to overcome this problem a limiter is applied before the differential decoder. This normalizes the envelope \( R(t) \) to unity for all \( t \). Thus \( y(t) \) now depends only on the cosine term of the equation.

4.2 GMSK Receiver Design on SPW Using a One-Bit Detection Scheme

Figure 4.3 shows the block diagram of the one-bit differential decoder as implemented on SPW. The same signal analysis as presented in Section 4.1 of this chapter can be applied to the one-bit detection scheme. To simplify the analysis, it is assumed that the signal structure applied to the one-bit differential detector has the form (Simon, Wang 1984)

\[
s(t) = A(t) \cos [w_o t + \phi(t)] \tag{4.8}
\]

where

- \( A(t) \) is the amplitude of the signal \( s(t) \)
- \( \phi(t) \) is the phase of the signal

and \( w_o \) is the center IF filter radian frequency.

The result of the one-bit differential encoder is to delay the incoming signal by one-bit period, \( T \), and to phase shift it by 90 degrees. The two operations are performed by the delay block and the complex conjugate block respectively.

Therefore we have the resulting equation
Figure 4.3 One-Bit Differential Decoder
A(t) is the change in phase per symbol time.

If we choose the carrier frequency $\phi(t)$, such that the product $\phi(t)T$ is an integral multiple of $2\pi$, then we have

$$sI(t) = \frac{A(t)A(t-T)}{2} \sin \left[ \omega_0 t + \phi(T) \right]$$

(4.9)

where

$\Delta \phi(t)$ is the change in phase per symbol time.

Therefore the sine of the phase difference gives an output that contains high frequency components due to multiplication, which are removed using a Butterworth lowpass filter. The output of the filter gives the data stream, which is applied to a threshold in order to make bit decisions. This decision threshold is kept at zero, i.e., we decide a "1" was transmitted if the input to the decision block is greater than zero and a "0" was sent if the input to the decision block is less than zero.

The reason a one-bit detector does not require a dc bias (the threshold is kept at zero) is because the value of $[A(t) - A(t-T)]$ for a given data pattern is negated for the complementary data pattern, and the "sine" function is an odd function of its argument. Equivalently stated, the values of the phase difference for the bit patterns "011" or "110" would be opposite in sign relative to the values of the patterns "100" and "001". Thus, a symmetrical eye pattern is obtained.
4.3 Bit Synchronizer

Bit synchronization is required to recover the clock signal, in order to make bit decisions on the output signal from the low pass filter block, shown in Figure 4.1. In the design of the GMSK receiver, decisions were made on the samples, continuously, and the use of a clock signal was required. However, to perform BER evaluation, a type of bit synchronizer is required. This is because the transmitted data, which is in the form of non-return-to zero (NRZ) pulses, must be compared with the received data.

The advantage of doing a simulation is that the start of a bit stream can be predicted. As a result, the transmitted and received bits can be aligned to check for bit errors. The synchronization problem arises when we need to set up the system in real time. Here the start of the bit stream received by the receiver is not known. Therefore it is virtually impossible to predict the start and end of individual bits. Due to the above reasons, a bit synchronization circuit is required.

The goal is to design a bit synchronization circuit that would meet the requirements of real time computations. In other words, we require a bit synchronization circuit that is not very complex and at the same time can derive the clocking signal. Two such circuits were implemented on SPW. One was the early late gate type of bit synchronization circuit and the other was a simple phase locked loop (PLL) circuit.

The details for generating the clock signal are shown in Figure 4.4. The parameters of the PLL are adjusted to generate a sinusoidal waveform at the
Figure 4.4 Clock Generation Circuit
required bit rate (Wolaver, 1991). The output is fed to a rising edge detector that outputs clock pulses at the received bit rate. This clock can then be used to extract the received bits by applying the threshold at the appropriate time.

4.4 System Setup for BER Evaluation:

The GMSK transmitter consists of a differential encoder, which is required for the two-bit detector scheme, and a GMSK modulator. The differential encoder is shown in Figure 4.5. The GMSK modulator, as shown in Figure 4.6 consists of a Gaussian premodulation lowpass filter, and an FM modulator with a modulation index of 0.5. The purpose of the encoder is to allow hard decisions to be made at the receiver end. The Gaussian lowpass filter (GLPF) is used to suppress the sidelobes and therefore reduces out-of-band spurious power to a great extent. The parameter that affects the performance of the system as far as the GLPF is concerned is the 3-dB bandwidth, $B_r$. This is normalized with respect to the symbol rate $T$, to give the product $B_r T$. The FM modulator is a simple voltage controlled oscillator (VCO) whose frequency is varied by the incoming signal.

The receiver block diagram consists of a non-coherent GMSK demodulator as discussed in Section 4.1 of this chapter. Additive White Gaussian Noise (AWGN) is added to the system as shown in Figure 4.7. The received and the transmitted bits are then fed into the error counter where they are compared, and the probability of error is computed as a result. A similar set up is achieved for the one-bit differential detection scheme by replacing the two-bit differential detector in the
randomip

\[ \boxplus \]

\[ x \]

\[ \text{hold reset} \]

\[ \text{out} \]

\[ Z \]

-16

\[ \text{outputenc} \]

**Figure 4.5 Differential Encoder**
Figure 4.5  GMSK Modulator
Figure 4.7 Overall System for BER Evaluation
GMSK receiver module with the one-bit differential detector as discussed in Section 4.3. The main difference in the transmitter for this set up is that an encoder is not required. Also, at the receiver end the decision threshold is maintained at zero level.

4.5 Comparison of Two-bit and One-bit Detection Schemes

A plot of the theoretical BER curve for the two-bit differential detection (Simon, Wang 1984) is used as a reference and compared with the data points obtained from the simulation. The resultant curve is plotted and is shown in Figure 4.8. A comparison of the theoretical plot for the two-bit detection, simulated two-bit detection, theoretical one-bit detection (Simon, Wang 1984) and simulated one-bit detection plots, are shown in Figure 4.9. From this Figure it is possible to see that a two-bit differential detector gives approximately 1-dB better performance than the one-bit differential detector. Therefore, based on the BER performance criteria, the two-bit differential detector is used for demodulation of the phase modulated data in the hybrid system.

4.6 Non-Coherent MSK

The use of the system setup for BER evaluation for demodulation of the GMSK signal can also be used for non-coherent MSK signal detection. The need for simulating a system using non-coherent MSK detection was two-fold: 1) To compare the results with the theoretically available BER curve for MSK detection;
Figure 4.8 Comparison of Theoretical and Simulated GMSK BER Plot (2-Bit)

Figure 4.9 Comparison of 1-Bit and 2-Bit Detection
and 2) To verify that coherent and non-coherent MSK BER curves do have a 3-dB difference in performance (Couch, 1990).

Non-coherent MSK is detection of a signal without having carrier synchronization. The transmitted signal has the same signal structure as discussed in the previous section. A complex waveform representation is used in this case. An MSK type of implementation can be seen as either a phase shift keying type of signal or frequency shift keying type of signal. In the coherent case the phase shift keying is clearly visible as the inphase and quadrature signals are separately created and used to modulate the corresponding carrier signal components. In the following case, the frequency shift keying type of implementation appears evident as frequency modulation results from a voltage controlled oscillator whose output frequency is governed by the input voltage. The input voltage is the incoming bit stream. The phase modulator (PM) modulator represents the inphase portion as a real number and the quadrature portion as a complex number. Thus, a transmitted signal of complex type is generated. This is an implementation similar to the GMSK type of transmitter. The fundamental difference being that the BT product of the Gaussian filter at the transmitting end is kept at a value of infinite bandwidth. Usually this is kept at 0.25 to 0.75 for a GMSK type of signal transmission.

The use of the two-bit differential detection scheme is employed for demodulation. A one-bit differential detection could also be used, but the two-bit differential detector provides better performance than the one-bit differential detector (Ogose, 1983). The receiver structure is the same as that used for the GMSK
demodulation with the predemodulation Gaussian filter having a BT product of 1.5. This value is used to give optimum performance (Ogose, 1983).

Gaussian noise is injected into the system and the BER curve is plotted. The theoretical plot of non-coherent MSK is evaluated from the following equation (Couch 1990):

\[ P_e = \frac{1}{2} e^{-\frac{1}{2} \left( \frac{E_b}{N_0} \right)} \]  

(4.14)

The theoretical and simulated plots are superimposed and are shown in Figure 4.10. The simulated plot closely follow the theoretical plot. Also a comparison of the coherent and the non-coherent MSK systems are shown in Figure 4.11. There is clearly a 3-dB to 4-dB performance loss when non-coherent MSK is used, verifying the theoretical results for this simulation.

4.7 Incorporating Doppler shift

With the verification of the GMSK transceiver structure designed on SPW, a closer look at the receiver performance under the Doppler effect must to be considered. Doppler effect comes into existence as a result of the receiver being placed on a mobile platform, in this case an aeroplane. The amount of Doppler shift depends on parameters such as transmitted carrier wavelength and velocity of the mobile platform. This value of shift in the carrier frequency can be easily calculated as both the above mentioned parameters, carrier wavelength and velocity of the vehicle is known to us.
Figure 4.10 Theoretical Non-Coherent MSK BER Plot

Figure 4.11 Comparison of Coherent and Non-Coherent MSK BER Plots
For the actual conditions the Doppler shift can be calculated as (Elnoubi, 1986):

Let $f_d$ be the maximum Doppler shift. We have, $f_d = \frac{\nu}{\lambda}$, where $\lambda$ is the carrier wavelength and $\nu$ is the speed of the vehicle. For the transmitter, $f_c$, the carrier frequency has a value of 135.6 MHz. Also $\lambda = \frac{c}{f_c}$, where $c = 3 \times 10^8$ (is the speed of light in m/sec).

We have, $\lambda = \frac{3 \times 10^8}{135.6 \times 10^6} = 2.212$ m.

For a plane moving at 77 m/sec, the Doppler shift would be given by an amount $f_d = 34.81$ Hz. The Doppler shift is incorporated in the simulation by varying the value of the complex spectral shifter by an amount as given by $f_d$. An important observation made during the simulation of the GMSK system needs to be mentioned. For a Gaussian receiver normalized bandwidth, $B_r T$ of 0.9 and the threshold being kept at 0.0985, the incorporation of Doppler has an adverse effect starting at 13 dB and for higher values of $\frac{E_b}{N_0}$. This is shown in Figure 4.12. The Gaussian receiver filter bandwidth was adjusted to 1.2 and the threshold was kept at zero. The resulting BER curve is as shown in Figure 4.13. From this Figure it is clearly seen that Doppler has no effect on the system but adjusting the threshold value and the Gaussian receiver bandwidth does cause a 1 dB loss in performance when compared to the theoretical curve whose parameters are adjusted to give optimum performance, these being a $B_r T$ of 0.5, a $B_r T$ of 0.9 and a threshold of 0.0985.
Figure 4.12 Plot of GMSK BER with Doppler Shift

Figure 4.13 Comparison of GMSK with and without Doppler
4.8 Conclusion

A GMSK transceiver model using two-bit and one differential detection methods were developed and simulated to generate the BER curves for such a system. The noise injected into the systems was AWGN and the probability of bit error was computed for each system. The curves for the theoretical and the simulated systems for the two-bit differential detection schemes were superimposed and are in agreement for the simulated system.

Also a comparison of the two-bit and one-bit differential detection showed that the use of a two-bit differential detector would improve system performance for the hybrid implementation. A non-coherent MSK system using the two-bit differential detection scheme is also discussed. The flexible design of the two-bit differential detection scheme allows a simple simulation of the respective system. A comparison was made between the coherent and non-coherent MSK system and a 3-dB loss in performance was obtained for the non-coherent MSK system. This was in agreement with the theoretical results.

The effect of Doppler on overall system performance was also studied for the GMSK system using two-bit differential detection scheme. A shift in the frequency of the transmitted signal was incorporated and a comparison of the transmitted and received bits was made. The resultant BER curve was plotted. The Doppler phenomena showed very little effect on the system performance. Therefore it is interpreted that Doppler shift in the transmitted signal will have very little effect on system performance.
Chapter 5
Hybrid Modulation Simulation

As mentioned earlier in this paper, weather information is available to the pilot via radio, using the VHF band for civil aviation. This is accomplished by amplitude modulation of radio frequency carriers in the VHF band. There are 720 channels spaced 25 KHz apart from 118.0 to 135.975 MHz. There are recommendations being made to reduce channel spacing from 25 KHz to 12.5 KHz so that more channels can be placed within this spectrum (Radio Technical Commission for Aeronautics, RTCA/DO-169).

The final goal of the hybrid modulation is to both phase and amplitude modulate the radio frequency carrier and to demodulate the voice and data signals at the receiving end. In Chapter 4 the design and performance characteristics of GMSK transceiver were given. In this section the overall hybrid system design and performance characteristics will be discussed using the GMSK transmitter to phase modulate the carrier signal. Previous simulations to determine bit error rates have been performed using MSK and QPSK signal structures but not GMSK type of signal structure.

5.1 Hybrid System Using GMSK Transceiver

An amplitude modulated carrier is given by the equation

\[ s(t) = A_s [1 + K_m m(t)] \cos (2\pi f_c t) \]  

(5.1)
where: $A_c$ is an amplitude coefficient (Volts)

$k_v$ is the amplitude sensitivity of the modulator

$f_c$ is the carrier frequency (Hz)

$m(t)$ is the modulating signal

A phase modulated carrier can be expressed as

$$s(t) = A_c \cos \left[ 2\pi f_c t + \theta(t) \right]$$  \hspace{1cm} (5.2)

where $\theta(t)$ is the phase modulation created by a modulating signal

Combining both phase modulation and amplitude modulation on the same carrier results in the following equation

$$s(t) = A_c \cos \left[ 2\pi f_c t + \theta(t) \right]$$  \hspace{1cm} (5.3)

Under ideal situations the two modulation techniques do not interfere with each other. However, under practical conditions, filtering and hard-limiting at both the transmitter as well as the receiver end cause an interference mechanism between the two modulations. Filtering at the transmitting end is performed to limit the bandwidth of the signal and at the receiving end to improve sensitivity. Also, hard-limiting is performed at the front end of the phase detector to remove the amplitude modulation on the signal. As a result both the amplitude and phase modulated signals suffers degradation.

Examining the spectrum of the MSK signal, as shown in Figure 5.1, it can be seen that the signal contains high frequency components that spread out over an infinite bandwidth. Using a filter to remove these high frequency terms causes variations in the amplitude envelope (Greenstein, Fitzgerald, 1979). This can be
Figure 5.1 Power Spectral Plot of Ideal MSK Transmitted Signal
seen by examining the received MSK signal for the case in which no amplitude modulation is done on the carrier signal and the case in which amplitude modulation, followed by filtering at the transmitting end and filtering at the receiving end is performed on the carrier signal, as shown in Figure 5.2 and Figure 5.3. Thus, bandlimiting causes envelope variations in the received signal that are not caused by amplitude modulation. Previous studies have suggested that the MSK type of phase modulation can be used for the hybrid system (Benelli, 1982). The reason for doing so is that the sidelobes of the MSK spectrum are small compared with QPSK and BPSK, and therefore will cause less degradation in the received signal as far as amplitude variation is concerned. With a GMSK type of phase modulation there is very little energy contained in the sidelobes as shown in the spectrum of a transmitted GMSK signal, with $B_i \cdot T$ of 0.75, in Figure 5.4. This modulation would have even a lesser effect on the amplitude variation of the received signal due to bandlimiting. However, there is a severe intersymbol interference due to the implementation of a GMSK type of phase modulation. Also since we are dealing with a non-coherent type of detection, there is still further degradation in the bit error rate for data transmission.

In order to simulate the hybrid system with GMSK as the phase modulation, the various parameters necessary were obtained from the previous work of Craig Parker (Parker, 1989). To retrieve the phase modulation, certain restrictions are imposed on the amplitude modulation index $\mu$ given as:

$$\mu = |k_r \cdot n(t)| < 1.0 \quad \text{for all time } t$$
Figure 5.2 MSK Received Signal without AM

Figure 5.3 MSK Received Signal with AM after Filtering
Figure 5.4 Power Spectral Plot of GMSK Transmitted Signal (Bt = 0.75)
For the ground based VHF transmitters used for aeronautical purposes, it is required to keep $\mu$ between 0.7 and 1.0 (Federal Communications Commission, 1987). For simulation purposes the modulation index was kept at 0.8.

The memory limitations of the available system and the computational time involved do not allow for simulation of the system at VHF frequencies. Therefore, the system was simulated at baseband. The specifications for the transmitter filter and the receiver filter were obtained from the work done by Benelli and Fantacci and are given below:

Transmitter Filter - 4th order Butterworth

3-dB Bandwidth of ±7.5 KHz

Receiver IF filter - 8th order Butterworth

3-dB bandwidth of ±5.0 KHz

5.2 Computer Simulation for BER Evaluation

The overall setup for the hybrid simulation is shown in Figure 5.5. The system is similar to the simulations performed previously to obtain the bit error rate probability curves. Here the carrier is both amplitude and phase modulated. The phase modulation is performed using the GMSK modulator as described in Section 4.3. A simulated voice data signal is generated by summing five sinusoidals given by (Benelli, Fantacci 1983):

$$m(t) = \sum_{i=1}^{5} a_i \sin(2\pi f_i t)$$  (5.4)
Figure 5.5 BER Evaluation for Hybrid System
where: \( m(t) \) is the simulated voice signal

\[ a_i \text{ are amplitudes (volts), and } f_i \text{ are frequencies (Hz) as shown in Table 5.1.} \]

The above voice signal was generated on SPW using five signal generators. These sinusoidal signals were then scaled appropriately with scaling factors given in Table 5.1. The resultant signal generated is as shown in Figure 5.6. The corresponding power spectral density is shown on Figure 5.7. Since there are five sinusoidal signals being generated at certain frequencies, we obtain five peaks in the power spectral density at the respective frequencies. Figure 5.8 shows the five sinusoidal generators connected to the scaling factors generating the resultant simulated voice signal.

To generate a signal as given by equation 5.1, the voice signal is multiplied by a scaling factor of 0.8. This is the value of the modulation index and needs to be limited between 0.7 and 1.0 as discussed earlier. The final signal forming the amplitude modulated signal is generated by adding to the resultant signal a DC gain of 1. Recalling that the simulation was performed at baseband, the carrier frequency, \( f_c \), is set to zero.

The amplitude modulated signal was multiplied by the inphase and quadrature components of the output of the GMSK transmitter. This is how the practical system would also be implemented. Before transmitting the signal, bandlimiting is performed. The transmit filter used for this purpose was a Butterworth lowpass filter of the 2nd order with 7.5 KHz 3-dB cutoff frequency, which corresponds to a
Table 5.1 Frequency Components in the Simulated Voice Signal and their Associated Weights

<table>
<thead>
<tr>
<th>Amplitude (volts)</th>
<th>Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>$2/9$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$1/3$</td>
</tr>
<tr>
<td>$a_3$</td>
<td>$2/9$</td>
</tr>
<tr>
<td>$a_4$</td>
<td>$1/9$</td>
</tr>
<tr>
<td>$a_5$</td>
<td>$1/9$</td>
</tr>
</tbody>
</table>
Figure 5.6 Voice Signal Generated for AM

Figure 5.7 Power Spectral Plot of Voice Signal
Figure 5.8 Voice Signal Generator
bandpass filter of 4th order with 7.5 KHz 3-dB cutoff frequency.

In order to obtain the bit error rate curves, noise was injected into the system. Complex Additive White Gaussian Noise with a mean of zero and a variance whose value was varied was used. Noise was injected at the output of the Butterworth lowpass filter as shown in Figure 5.5. The output of the complex adder forms the received signal. The received signal was fed to a lowpass 4th order Butterworth filter with 5.0 KHz as the 3-dB cutoff frequency. The amplitude modulation was removed by using an RF hardlimiter followed by a lowpass Butterworth filter of order 6 and 3-dB cutoff frequency of 2500 Hz, this is represented as the AM_DEMOD block. The details of this block are shown in Figure 5.9.

The output of the Butterworth lowpass filter was fed into the GMSK receiver block whose operation is described in Section 4.1. The output binary data was then compared with the input binary stream to obtain the bit error rate curves. As mention above, this was accomplished by varying the variance of the Complex Gaussian noise generator to obtain various points on the bit error rate curve. A simulation of about 100000 bits was done. This gives a probability of bit error of about $10^{-4}$ of accuracy.

5.3 Hybrid System using an MSK Coherent Transceiver

The use of a GMSK transceiver structure for the hybrid modulation is a completely new idea. To verify the steps of design and their compatibility, no
actual results are available as far as using a GMSK transceiver for the hybrid modulation is concerned. Previously, logical steps were followed for the GMSK transceiver design simulation and the resultant BER curves for the GMSK transceiver design were verified with the theoretical curves (Simon, Wong 1984).

However, we do have the BER curves for the hybrid modulation using MSK signal structure for phase modulation/demodulation (Benelli, 1982). The use of the results presented in this paper could be used to verify the simulation results as far as using MSK coherent detection for the hybrid system is concerned. The total system set up for the hybrid system simulation using MSK coherent detection is shown in Figure 5.10. The system set up is similar to the one described in Section 5.2. The use of the MSK modulator/demodulator as described in Chapter 3 of this paper is applied.

5.4 Performance Evaluation

The resulting BER curve for the case of infinite-bandwidth and constant envelope data modulation using MSK and that for the hybrid system using MSK is shown in Figure 5.11 (Note: The various BER plots, namely Figure 5.11 - Figure 5.16 are presented at the end of this Chapter). The computer simulations show a loss of about 2-dB to 4-dB with respect to the case of infinite-bandwidth and constant envelop data modulation using the MSK signal structure. This is in agreement with the results obtained in the paper presented by Benelli (Benelli, 1982). Therefore, we should get about 2-dB to 4-dB loss approximately for the
hybrid system using GMSK phase modulation with respect to the GMSK system transmitted with infinite bandwidth and a constant envelope.

The comparison of the BER curves for hybrid modulation using GMSK phase modulation/demodulation and the theoretical curve for infinite-bandwidth and constant-envelop GMSK modulation are shown in Figure 5.12. Also, a comparison of bit error rate curves of the implemented GMSK system, theoretical GMSK system and GMSK system with amplitude modulation are shown in Figure 5.13. From Figure 5.13 it was interpreted that the GMSK system with amplitude modulation provides a 2-4-dB loss in the system when compared with the GMSK system without amplitude modulation.

With the variation of the 3-dB bandwidth product, $B \cdot T$, of the transmitting Gaussian filter, the spectrum of the transmitted signal varies as discussed in Chapter 4. The same variations were employed for the hybrid system and the respective BER curves were plotted, shown in Figure 5.14. A value of 0.75 for $B$, which is the 3-dB bandwidth product of the transmitting Gaussian filter, gives the best performance when compared with the other two values of 0.5 and 0.25 being considered. This is because there is less intersymbol interference in the transmitted signal.

A comparison of the BER curves for the hybrid system using non-coherent MSK phase modulation/demodulation and the hybrid system using GMSK phase modulation/demodulation using $B \cdot T$ of 0.75 are shown in Figure 5.15. Although the non-coherent MSK incorporated in the hybrid system does give a slightly better
BER performance then the GMSK modulation hybrid system, the use of the GMSK modulation/demodulation is preferred due to restrictions imposed on the transmitted signal as far as bandwidth is concerned and improved voice signal to noise ratio.

The two-bit detection provides better performance when compared to the one-bit detection scheme as discussed in Section 4.5. This was however for the infinite bandwidth case without amplitude modulation. The one-bit detection scheme was also used for the hybrid system for phase demodulation and the BER curve is as plotted in Figure 5.16. From the plot it is evident that even for the hybrid system two-bit detection does provide a better performance.

5.5 Conclusions

A detailed analysis of the hybrid system using GMSK phase modulation/demodulation has been presented in this chapter. Since the BER curves were not available for the hybrid system using such a modulation technique, a hybrid system using MSK phase modulation/demodulation was simulated. The results for the BER curves of this simulation were available and were similar to those obtained using SPW. It was interpreted that using the GMSK phase transceiver structure for the hybrid system, the loss in performance should be similar to that for the MSK system. This was confirmed by the BER curves obtained from a simulation.
Figure 5.11 Comparison of MSK BER with and without AM

Figure 5.12 Comparison of GMSK Theoretical and Simulated with AM
Figure 5.13 Comparison of GMSK Theoretical and Simulated with & without AM

Figure 5.14 Comparison of Theoretical & Simulated GMSK BER Plots for various BT
Figure 5.15 Comparison of GMSK and MSK Systems with AM

Figure 5.16 Comparison of 2-bit & 1-bit Detection Schemes for the Hybrid System
CHAPTER 6

Hybrid System Implementation

With the completion of the GMSK phase modulator/demodulator for the hybrid system the next step was to implement the system in real time. As mentioned in Section 1.3, CGS was used to develop the real time receiver. This receiver can demodulate the phase modulated part of the hybrid signal. A TMSC320C30 DSP microprocessor board was used, together with CGS, to produce a real time Gaussian phase demodulator. A step-by-step procedure was followed to conceive the entire hybrid modulation/demodulation system.

6.1 GMSK Transceiver Implementation at Baseband

The overall setup for the implementation of the GMSK transceiver structure is shown in Figure 6.1. The simulated system as described in Section 4.4 is used with CGS to generate a C program on the Workstation itself. The Workstation is connected to two PC modules, via an Etherlink connection, which have the DSP microprocessors installed. PC 1 forms the transmitter section of the system and does the work of the phase modulator for the hybrid signal. PC 2 forms the receiver part of the system and is used to demodulate the phase modulated data. The DSP board on PC 1 was used to generate inphase and quadrature components of the GMSK signal. The DSP board has digital-to-analog converters (DAC) which convert the computed digital signal into a real time analog signal. These signals
Figure 6.1 Overall Setup for Testing of BaseBand Hybrid System Phase Transceiver
were then transmitted, initially using a cable, to the analog to digital converter (A/D) of the DSP board located on PC 2. The DSP board on PC 2 is used as a demodulator and the received demodulated bit stream is visible on the screen of PC 2.

In theory, both the transmitter and the receiver section could be implemented in real time. However, the processing was required to be carried out in real time using the existing DSP boards. This required the system design to meet the processing speed of the DSP board. The use of a GMSK transmitter using CGS was not a feasible solution because of two reasons: 1) The computational speed of the DSP board was not fast enough, using the C program generated by CGS, to output the GMSK signal in real time, 2) The implementation of the Gaussian filter on SPW Workstation needed modifications.

Due to the implementation of the Gaussian filter as constructed on SPW, the transmitted GMSK signal showed instability. Although such a transmitter implementation is good for simulation purposes, it would show instability if used for real time purposes (Murota, 1981). The GMSK signal lost its structure after a few minutes of transmission. An alternate DSP-implementation of a GMSK transmitter was available from prior research on the hybrid signal (Akos, 1992). The transmitter however, as implemented by Akos, did require some modification. This transmitter did not incorporate any encoding on the incoming bit stream. A simple C program was implemented that differentially encoded the incoming data bits.

The receiver section was completely implemented using CGS. The
demodulated data bits were scrolled on the PC screen and were compared with the transmitted data bits. To confirm that the system is working satisfactorily, a known data pattern was transmitted and was successfully demodulated by the receiver.

6.2 GMSK Transceiver Implementation at RF

A systematic verification of the implemented system in real time was followed. Since the system worked at baseband as mentioned in the preceding section, an RF (radio frequency) implementation of the system in real time could be implemented. This requires modulating a carrier signal typically in the Megahertz (MHz) range. The target frequency at which this system will be implemented, requires the use of a carrier signal at 135.875 MHz. This is, however, a specific application and requires the use of components with specifications not commonly available. However, components such as demodulators, limiters, etc. which operate at a standard frequency are readily available and can be used for laboratory purposes. The use of filters, demodulator and hard limiter to test the system was made at a standard 70 MHZ frequency, available from a popular RF components sales company. A signal generator, HP 8640B, was used to generate both FM and AM modulated carrier signal at 70 MHZ. Therefore, a signal having both FM and AM was generated at RF. A Marconi signal generator, model 2018, was used to generate the local oscillator frequency at 70 MHz for the demodulator. The overall setup for the hardware test implementation of the hybrid system is shown in Figure 6.2.
Figure 6.2 HYBRID SYSTEM SETUP FOR TEST EVALUATION IN REAL TIME
PC 1 acts as a transmitter, generating the modulating signal for the phase modulation of the hybrid system. This represents digital data containing the weather information. The DSP board generates the analog signal that is input to the signal generator that performs simultaneous AM and FM on the carrier signal. The FM is input externally using the analog signal generated by the DSP board while the AM signal is generated internally. The resultant RF signal is fed to a bandpass filter. This filter is used only for test purposes and simulates a transmit filter. The use of this filter in the actual transmission application is to confirm to FCC spectral limits. Since we were testing the system in the laboratory, this filter does not have critical significance.

The hardlimiter is used to remove the AM on the carrier signal. The hardlimiter does require a DC source to inject a control current that can be used to vary the amplitude of the input signal (RF Designer's Handbook, Minicircuits 1994). Filter2 removes the high frequency components that are introduced in the signal because of hardlimiting. To obtain the signal at baseband that would allow the DSP board to demodulate the digital data in real time, the I/Q demodulator is used. A local oscillator generates the local carrier signal at 70 MHz. The output of the demodulator is fed to the DSP board (DSP2). This converts the analog signal into digital samples and the demodulated data can be either scrolled on the screen or saved to a file on the Workstation.
6.3 Conclusions

The simulation and real time implementations of the hybrid system have been discussed in this chapter. A step by step procedure was followed to implement the GMSK transceiver structure in real time. This was done at baseband to verify the operations of the transceiver structure in real time. Once the operation of the system at baseband was successfully tested; the overall hybrid system for test purposes was set up at RF. Both AM and FM were imposed on a single carrier waveform using the HP 8640B signal generator. Hardlimiters, filters and demodulator were also used to set up a model of the actual system.

The verification of the system performance was made by saving the demodulated data bits to a file on the Workstation. The capabilities of SPW and CGS were made for this purpose. A known data pattern was transmitted. The demodulated data bits were stored on the Workstation. The two data patterns were compared and were found to be identical. Therefore, we conclude that the overall system set up for test purposes operates satisfactorily.
CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

The use of a sophisticated software program, SPW, and the design techniques that can be used to implement signal processing and communication systems in real time were discussed in this paper. CGS is a subset of SPW and allows the generation of a C program, for the designed system, which can be downloaded onto a DSP microprocessor board, therefore allowing the implementation of the system in real time.

The use of SPW and CGS were employed to design and implement a digital transceiver structure used for the hybrid modulation system. This system is currently proposed to supply weather data information from a ground station to aircraft. With such a system, the existing AM transmitter requires only a straightforward modification, and a phase demodulator can be incorporated in the aircraft to demodulate the weather data. This would in effect double the spectral efficiency of the existing channels.

Various digital phase modulation/demodulation systems that can be used in the hybrid system have been discussed. They have been simulated and evaluated based on the respective BER curves. These simulated BER curves were compared with the theoretical curves and shown to match the theoretical curves closely. A particular phase modulation technique, namely the GMSK modulation, which has been proposed by Dennis Akos at Ohio University Avionics Engineering Center, has
been evaluated in detail.

The Doppler effect is major source of degradation in performance of the phase modulation/demodulation system. This is because the platform supporting the phase demodulator is mobile (aircraft), and therefore induces Doppler shift into the system. This effect has also been simulated. The receiver design parameters were adjusted to accomplish a tradeoff between optimum performance and incorporation of Doppler. The designed system shows a 1 dB performance loss due to Doppler shift. The GMSK phase modulator/demodulator was implemented in real time. The use of a GMSK transmitter previously constructed was employed. The designed receiver was used to demodulate digital data as generated from a signal file and the demodulated data bits were displayed on the PC screen. The C program generated by CGS for the DSP board allows for the data bits to be stored in a signal file on the Workstation. This was done and the data bits were compared to those transmitted and were found to match.

The next step was to design a test system for hybrid modulation and demodulation at RF. The simulated system was implemented in real time using filters, hardlimiters and demodulators as discussed in Chapter 6. The digital data was demodulated using the DSP board as a demodulator at baseband. The data bits were again stored in a signal file on the Workstation and were in agreement with the transmitted bits.

Future work requires refinement of the above hybrid system in real time. In order to display the weather data, the demodulated data bits from the DSP board
need to be transferred to another PC that would contain the data decompression algorithm (Parker, 1989). A straightforward implementation is to interface the serial output of the DSP board with the RS232 serial port of the PC. This, however, requires an hardware interface to be constructed. Also, the amplitude modulated signal can be demodulated by a simple demodulator circuit, for test purposes. With the increase or decrease of the data rate of the phase modulating signal the degradation in the demodulated voice signal can also be observed.

The actual implementation requires the use of transmitter and receiver filters with specifications as mentioned in Section 5.1. Using a White Noise generator circuit, along with the serial interface on the DSP boards, BER evaluations can be performed in real time for the actual system set up. This can be done using components with parameters chosen to meet the actual hybrid system implementation. Thus an actual real time testing of the VHF aeronautical band can be implemented using the hybrid modulation technique.
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